THE WORLD OF CHEMISTRY

Program #9

MOLECULAR ARCHITECTURE

Producer John Ketcham

Air Script: October 31, 1988

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Annenberg/CPB Project Logo and Music

Funder Credits

MONTAGE: City scenes, nature, glider, crystals, graphics

NARRATOR (MUSIC and NAT SOUND under):
All matter is made up of atoms, ions, and molecules, from our cities to the seas. Even the air is made of molecules. Just as we use particular building materials, nature uses only certain molecules while creating amazing variety. The natural world is highly selective when building its own molecular architecture.

SUPER: MOLECULAR ARCHITECTURE

THE WORLD OF CHEMISTRY OPEN: Montage, Music, Logo

RH at construction site

ROALD HOFFMANN (SYNC):
I know what's gone into the construction of that building, structural steel and wood, bricks and concrete. In fact, all the buildings around here are made of the same materials. Our achievement as human beings is to use the same simple building blocks to assemble an immense variety of structures that serve us. It's the same in chemistry. We've been given about a hundred building blocks. That's the atoms. They come in a variety from hydrogen to uranium. And, from these simple building blocks, nature has shaped the thousands and millions of molecules that are necessary to make life and the earth function, that make for the difference or the similarity between you and me. And then, also in the laboratory, we chemists, for good measure, add a million or so new molecules every year. We have learned the rules by which atoms are connected up to each other to form molecules. But it isn't only the way that the atoms are bonded to each other. It turns out it is the three-dimensional shape of molecules, their architecture, that governs chemistry.

MONTAGE: Shapes, flames, bubbles, graphics, sugar, graphite, diamonds, farm machinery, cotton, natural world

NARRATOR (MUSIC and NAT SOUND under):
All of the shapes surrounding us, whether synthetic or natural, and how they behave, whether they burst into flame or freeze, are determined by the bonds holding them together. And it is the nature of the atoms and how they form chemical bonds which determines how molecules are made. Substances can have the same number and same kinds of atoms and yet be different. Graphite and diamonds are both pure carbon, they're just bonded differently. Aspartame -- the molecule NutraSweet -- has a mirror-image molecule that tastes bitter. Only a variation in the molecular shape makes corn starch vastly different than the cellulose in cotton. How can this be? Molecules with the same numbers and kinds of atoms, but with different spatial arrangements, are called isomers. These different arrangements can result in significant differences in properties, which have an important impact on the natural world. To understand the implications of this, let's look at the atom common to all living things, carbon.

GRAPHIC: Carbon bonding

NARRATOR (MUSIC under):
This is an unbonded carbon atom. The valence electrons are arranged so that the bonds point to the corners of a tetrahedron. Four hydrogen atoms can bond with carbon, forming methane. Two tetrahedral carbon atoms can join together with a single bond, forming the molecule ethane. Longer molecules, built with single bonds, like ethane, will form long, straight chains. And because they can't accept any more hydrogen atoms, they're said to be saturated. Carbon can form double bonds, too, and when it does, the molecule will have a different shape. Notice because of the carbon-carbon double bond, this molecule, ethylene, has fewer hydrogen atoms than does ethane. More hydrogen could be placed there. So this molecule is said to be unsaturated.

Shots of deep fried foods, people eating, exterior: Johns Hopkins Hospital, Donna Sorensen with patient in hospital

NARRATOR (NAT SOUND under):
Saturated and unsaturated are terms we use to describe the fats and oils we eat, because edible fats and oils contain single and double bonds. The Johns Hopkins Hospital in Baltimore, Maryland. (cont.)

NARRATOR cont:
Donna Sorensen is a clinical dietician here. One of her patients, Mr. Agee, has been hospitalized because of high levels of cholesterol. He is abnormally sensitive to fats and oils in his diet.

Donna Sorensen with patient in hospital

DONNA SORENSEN (VO/SYNC):
Fish is excellent. Do you ever eat fatty fish? All of the foods that Americans tend to like, fast foods generally you will have some fatty acid. They range from margarine,

INTERVIEW: Donna Sorensen, clinical dietician, Johns Hopkins Hospital, Baltimore, Maryland

SUPER: Donna Sorensen

pastries made with shortening, cookies, french fries that are fried in these kinds of shortenings, any of the snack, fried snack foods are high. Even bread.

MONTAGE: Cooking with fats and oils, pastries, fast food, oils, shortening

NARRATOR (NAT SOUND under):
Most of us eat fats and oils every day. It's fat that makes meat taste good, and fat makes pastries tasty. And we need fat. We burn it for energy. Fats and oils are compounds of glycerine and fatty acids, and there's bad fat, saturated fat, and good fat, unsaturated fat. (cont.)

NARRATOR cont:
The differences between the two are those carbon bonds holding them together. Professor John Kinsella, a food chemist from Cornell University.

INTERVIEW: Dr. John Kinsella, food chemist, Cornell University

SUPER: John Kinsella

DR. JOHN KINSELLA (SYNC):
These are two fatty acid molecules that occur abundantly in nature. As I can say, this is a typical saturated fatty acid, it's a straight linear molecule. Saturated means that all the valences of the component carbons are fully satisfied or saturated. The introduction of one double bond results in a bent or a curved molecule. This is the bent molecule. And this tends to be, have motion and tends to be liquid or fluid at normal temperatures.

GRAPHIC: Architecture from the carbon double-bond

NARRATOR (MUSIC under):
To see how the carbon double-bond determines the shape of the fatty acid molecules, let's look at the electron clouds of ethylene. Three of the bonding electron pairs around each of the carbon atoms are directed towards the corners of a triangle. (cont.)

NARRATOR cont:
The remaining bonding pair of electrons exist in two clouds, one above, and the other below the molecule. Rotation around the double bond is prevented, and when larger molecules, like fatty acids, have double bonds like this, they may be bent.

Shots of oils, margarine and shortening factories

NARRATOR (NAT SOUND under):
What starts out as soybean oil soon becomes margarine, or solid vegetable fat. Soybean oil is full of bent unsaturated molecules. It can be turned into margarine by adding hydrogen to it and then blending it with other oils and milk products. The more hydrogen, the more saturated the molecules, the more solid the fat. That's because the hydrogen opens the double bonds, forming new bonds and straightening the molecules.

DS in lab

DON SHOWALTER (SYNC):
This is vegetable oil, soybean oil. I would like to change the geometry of that molecule in there so it becomes a solid? Take the kink out. How can I do that? Hydrogenation. What I would do is put some of the oil into this flask, mix some palladium catalyst, the black material in there, and pass hydrogen gas through the mixture. (cont.)

DON SHOWALTER cont:
Let's do that. I'm gonna push the hydrogen bubbler down into the mixture. Alright. You see the hydrogen gas coming in there. Alright. Now, this reaction is gonna take quite a bit of time before we're gonna see any product. Hey look! It's turned solid. Now, how did that happen? Well, by adding hydrogen, we've converted the double bond to two single bonds, saturating the molecules. We've produced a new substance, fat. Now, if you would extract the catalyst out of there, you would get a substance that looks just like this. This is a vegetable fat, shortening.

Food in deep fry basket

NARRATOR (NAT SOUND under):
It's the straight saturated molecules which worry food chemists like Professor Kinsella.

INTERVIEW: Dr. John Kinsella cont.

DR. JOHN KINSELLA (SYNC):
It is better to eat more bent molecules than straight molecules. Generally the recommendations are that we reduce overall consumption of fat, and that we carefully control the amount of straight molecules, saturated fatty acids that we consume.

Cooking deep fried doughnuts

NARRATOR (NAT SOUND under):
According to Professor Kinsella and health officials, it's the straight saturated molecules that cause health problems.

INTERVIEW: Dr. John Kinsella cont.

DR. JOHN KINSELLA (SYNC):
One of the risk factors involved in heart disease is the amount and type of fat that a person consumes.

Cooking deep fried doughnuts and chicken, people eating fried chicken

NARRATOR (NAT SOUND under):
The shortening used in cooking donuts, french fries, and chicken is loaded with the straight saturated molecules. Shortening has its advantages: a longer shelf life, higher cooking temperatures. But as we eat more deep-fried food and exercise less, worries about our health mount. But there's more. Unsaturated molecules can also be straight.

GRAPHIC: Unsaturated fatty acid isomers

NARRATOR (MUSIC under):
There are two isomers, geometric isomers of the unsaturated fatty acids. The trans-isomer is straight, while the other, the cis-isomer, is the bent molecule.

Shots from margarine factory

NARRATOR (NAT SOUND under):
It's during the hydrogenation process that some of the cis-molecules, instead of adding hydrogen at the double bond, are converted into trans-isomers. These trans fatty acids are straight, and they help other saturated molecules stack together. In fact, they act just like a saturated molecule in fats, like margarine and shortening. That's why there's some concern over the impact of trans fatty acids on health, even though they are unsaturated.

Donna Sorensen with patient in hospital

DONNA SORENSEN (VO/SYNC):
I think the evidence is quite clear now that eating a lot of fat, and, in particular, saturated fat, is detrimental to our health.

INTERVIEW: Donna Sorensen cont.

We know that saturated fats raise cholesterol levels. There's now an hypothesis that transunsaturated fats may also raise cholesterol levels.

Family eating at dinner table

NARRATOR (NAT SOUND under):
While the impact of transfatty acids on our health is being debated, most everyone agrees we should eat less fat. But beyond these geometric isomers there are other isomers with more profound relationships with living things.

RH at mirror in health club

ROALD HOFFMANN (SYNC):
The same and not the same. That's the basic tension underlying relationships between human beings. And it's also the source of richness, variety and control in the molecular world. We've just talked about two molecules of a fat that have the same number of carbon and hydrogen atoms that are bonded in the same way, and yet they're somehow different. And the reason for the difference is one is straight and the other one is bent. That difference in shape translates into their chemical and biological properties. Molecules are exquisitely specific. Differences between them even more subtle than that between geometric isomers can be a matter of life or death. Even as subtle a difference as that between a left hand and a right hand, between a molecule and its mirror image.

MONTAGE: Sugar cane fields, microscopic cells, sugar cane in greenhouse

NARRATOR (MUSIC and NAT SOUND under):
Molecules produced by living things, like the sugar in the sugar cane, or proteins in cells, all have a definite shape. But sugars and amino acids, and other molecules, have isomers which are mirror images. They are built as the left hand is to the right hand, the same, but different.

GRAPHIC: Optical isomerism

NARRATOR (MUSIC under):
These two structures are mirror images of each other, and they can't be superimposed over one another. No matter how we turn them, the atoms of one will never exactly correspond to the atoms of the other. These are called chiral-molecules, chiralmeaning "hand" in Greek. If these two molecules have the same molecular formula, how can we tell them apart? Amazingly, chiral-molecules rotate the plane of polarized light, and so they are also called optical isomers.

DS in lab

DON SHOWALTER (SYNC):
These two disks are polarizing filters. The light source, back here, is a sodium vapor lamp. It emits light of a single wavelength. Now the polarizing disks act like a picket fence and filter out all the waves except those that can go through the spaces between the pickets. So the light that comes out is now plain polarized light. If I rotate this forward polarizing disk, I can reach a point where the light is blocked out by this forward disk. Now I'm going to put a flask that has distilled water in it in there. Do you notice any difference? Not much light coming through there, a little bit of scattered light. Now I'm gonna put a solution of sucrose, table sugar, in there. Oh, look at the difference there. Your light is coming through that forward disk now. So sugar molecules dissolved in the water have rotated the light waves so that now they come through the forward disk. Now, if I rotate this a little bit to the right, I can block that light out again, to show you how much it's rotated. That's what we mean when we say that table sugar is optically active. And so are most of the molecules we're made of.

Cells under microscope, computer graphic

NARRATOR (MUSIC under):
In living things, chiral-molecules exist in only one form or the other, but not both, either D or L. Sugars are D, for dextro, or right-handed, and amino acids are L, for levo, or left-handed. Historically, D and L referred to the direction polarized light was rotated. But if only one, and not both, occur naturally, how did the selection of one molecule over another begin? And what are the implications? Nobel Laureate, Christian Anfinsen.

INTERVIEW: Dr. Christian Anfinsen, Nobel Laureate

SUPER: Christian Anfinsen

DR. CHRISTIAN ANFINSEN (SYNC):
Now, how to start in the first place is anybody's guess. It's been assumed that some, some naturally occurring minerals, for example, might have been involved in binding one form and not the other form, and thereby building up the concentration of the form that we have now, so that when life started it was stuck with that form.

Bottles and aspirin on assembly line, chemist working in lab

NARRATOR (NAT SOUND under): Living things not only produced just one form of chiral-molecules, they can only use one form. Synthetic adrenaline, taken by asthma sufferers, must be the L form. D won't work. L-dopa is a medicine for Parkinson's Disease, not D-dopa. And only L synthetic morphine will alleviate pain.

INTERVIEW: Dr. Christian Anfinsen cont.

DR. CHRISTIAN ANFINSEN (SYNC): In nature, of course, we're stuck pretty much with one isomer. The world has been so evolved that, that living things, in general, are composed of one, one of the two possible mirror images of the basic compounds. The most important word would be "specific," meaning the whole problem in biology is specificity. And since everything that goes on in living cells is carried out by enzymes, it's important that the enzymes see only one form. As a matter of fact, if an enzyme works on one form, say the correct L form of an amino acid, it will be inhibited by the D. Things would stop dead if gluc -- all the glucose in the world suddenly became the wrong isomer.

DS in lab

DON SHOWALTER (SYNC):
A common property of living organisms is their ability to distinguish between D and L forms of optical isomers. Let me show you an example of that. I've got a setup here where I put distilled water into this flask. I put the L-glucose in this flask, and D-glucose into this flask. I also added an equal amount of yeast to each of the flasks. That's our living organism. Now, if the yeast reacts with the glucose, it will cause fermentation, which will then give off carbon dioxide, and the carbon dioxide will come through the tube and then into the water and you should see some bubbles. Let's check out and see what's happening. In the first one, distilled water, nothing's happening. That's what we thought. That's our control. Here is the L form of glucose. Look over here, no bubbles, no reaction, no fermentation. But look over here. Look at this flask. It certainly fermented. And look over here at the carbon dioxide being generated. So the yeast has reacted with the D form of glucose but not with the L form.

Desert cliffs, archaeological dig

NARRATOR (NAT SOUND under):
Amino acids, which are L, are used by all living things in metabolism. But when cells die, their proteins begin to decompose, breaking into amino acids. In the absence of life, some L-molecules can become D. Dr. Ed Hare of the Carnegie Institute.

INTERVIEW: Dr. Ed Hare, Carnegie Institute

SUPER: Edgar Hare

DR. ED HARE (SYNC):
However, when that process stops, when the living process stops and there are no longer building up materials, then nature tends to a mixture of D and L amino acids. So the downgraded part, when you're breaking down proteins, leads ultimately to a mixture of L and D amino acids. And this process is called racemization.

Chemists in lab, close ups of test tubes, graphing, meteorite study on top of Chilean mountain

NARRATOR (NAT SOUND under):
Racemization can be measured. L and D molecules both rotate polarized light, but in opposite directions. If the two are mixed together, they start to cancel each other out. (cont.)

NARRATOR cont:
So the degree of rotation of the polarized light depends upon the proportion of the L to D amino acids in any given sample. If the amounts are equal, there is no rotation at all. Because that proportion changes slowly through time, from the moment the cell dies, Dr. Hare believes, by measuring a sample's rotation of light, he can date fossils. As Dr. Hare perfected his technique of looking into the past, another tantalizing application emerged. In 1969, a meteorite fell to the earth in Chile. It wasn't made of iron and nickel, like most meteorites. This one had carbon in it.

INTERVIEW: Dr. Ed Hare cont.

DR. ED HARE (SYNC):
Carbon-containing objects from outer space. What does it mean? Does it mean there's life out in outer space and this represents a planet like Earth, that developed life and then blew up, or some -- hit into a, another object, and these meteorites are relics from this? That was one idea. Or do these represent a cumulation of interstellar matter producing organic matter?

Close ups of testing meteorite samples in lab

NARRATOR (NAT SOUND under):
Dr. Hare analyzed pieces of the meteorite's core. He discovered amino acids in one of the samples, but there was no rotation of polarized light. The sample was evenly mixed L and D.

INTERVIEW: Dr. Ed Hare cont.

DR. ED HARE (SYNC):
What did this mean? Did this mean that they were originally organic matter that had all L or D amino acids and they were racemized? That's one possible explanation. The other possible explanation is that we're seeing some of the early stages of pre biology, that is, the accumulation of amino acids by non-biological processes.

Close ups of testing meteorite samples in lab

NARRATOR (NAT SOUND under):
He looked further. The first core sample hadn't rotated the plane of polarized light. Another sample, taken from another place on the meteorite, did. The mystery deepened.

INTERVIEW: Dr. Ed Hare cont.

DR. ED HARE (SYNC):
Are we seeing essentially Earth's contamination superimposed on a racemic mixture of amino acids, or are we seeing a process in which we did have living organisms that were based on the same L-amino acid configuration that we know here on Earth that has racemized but not in all of its fractions. There are still some fractions that show a preponderance of L. More work needs to be done on this, and I'm not ready to say the jury's in.

SUPER: MOLECULAR ARCHITECTURE

MONTAGE: Program graphics, margarine factories, lab demonstrations, microscopic organisms

NARRATOR (MUSIC under):
To review: Molecular geometry depends on the number of electron pairs around the central atom and how these pairs are bonded. Molecules having the same kinds and numbers of atoms can have different shapes and properties. These are called isomers. The lack of rotation around the double bond is the reason for the existence of cis and trans isomers. These are geometric isomers. Certain molecules have a non-superimposable mirror image. (cont.)

NARRATOR cont:
These are optical isomers because they rotate the plane of polarized light. D and L optical isomers rotate the light in opposite directions. It's extraordinary that living organisms produce and use only one kind of optical isomer.

RH in vineyard

ROALD HOFFMANN (SYNC):
The connection between optical activity and molecular structure was made by a 26-year-old French chemist in 1848, but what a 26-year-old. Louis Pasteur went on to show that microorganisms cause disease and fermentation. He invented a vaccine for rabies and anthrax, and a process called pasteurization, that we still use to this day. He saved the wine and silk industries of France. But what he did in 1848, early on in his career, has something to do with the place where I'm at. This is Plains Cayuga Vineyards. And in wine, there come out occasionally crystals of a salt of an acid in wine, tartaric acid. Now, later on, in the winemaking process, there is another acid that comes up called racemic acid. It was known already in Pasteur's time that racemic acid and tartaric acid had the same chemical formula, C4H6O6. But whereas tartaric acid rotates the plane of polarized light the way many natural substances do, racemic acid does nothing to that light. Pasteur was intrigued by this. (cont.)

ROALD HOFFMANN cont:
He looked at crystals of racemic acid under a microscope. To his amazement, he saw that there were two mirror image crystal forms. He separated those tiny crystals painstakingly, with tweezers. He made solutions of them and measured their optical rotation, and he found that one of the crystal forms rotated the plane of polarized light exactly the same way tartaric acid did, and the other one did it in the opposite direction. So racemic acid turned out to be an equal mixture of two forms of one and the same molecule, which rotated light in opposite directions. This finding was tremendously important. It showed that the optical activity of molecules was something intrinsic to the molecules, that it had to be sought, that handedness, at the level of the molecule. As ingenious as he was, Pasteur did not come up with a molecular model for the source of the optical activity. It took a quarter of a century, two equally young chemists, a Dutchman, van't Hoff, a Frenchman, LaBelle, to suggest that optical activity is based on carbon being tetrahedral. And this was done forty years before anyone in the world ever saw a carbon atom. How do we find out the shapes of molecules, that carbon is tetrahedral? How do we interrogate molecules? Join us next for "Messages From Within."

Credits, Closing Montage, Closing Music

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